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Applications using a picosecond 14.7 nm x-ray laser

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Abstract: We report recent application experiments on the LLNL COMET tabletop facility using the picosecond, 14.7 nm Ni-like Pd x-ray laser. This work includes measurements of a laser-produced plasma density profile with a diffraction grating interferometer.

1. Introduction

X-ray lasers have progressed rapidly towards higher efficiency, reduced size, low cost and high repetition rates with the development of tabletop pump sources [1-4]. The x-ray laser characteristics allow the pursuit of various applications including the determination of the properties of materials and interferometry of high temperature plasmas. In the latter case, Da Silva and co-workers, utilizing multilayer beam-splitters in a Mach-Zehnder interferometer, first demonstrated soft x-ray laser interferometry at 15.5 nm using the NOVA generated Ne-like Y laser to probe large 1-mm-scale plasmas [5]. More recently, Rocca and co-workers have established the 46.9 nm Ne-like Ar capillary discharge x-ray laser as a tabletop interferometric tool for plasmas [6,7].

Short pulse duration for the probe is one of the most important characteristics for performing interferometry on a rapidly evolving plasma. Attwood *et al.*, some years ago, were able to successfully determine plasma density profile steepening at high intensities using a 266 nm, 15 ps duration probe [8]. The short 15 ps pulse was essential for probing close to the target surface to freeze plasma motion. A short pulse x-ray laser also has the advantage of shorter wavelength. This allows the x-ray laser to access large plasmas at high density with less deleterious effects of absorption and refraction that strongly limit the applicability of visible or UV probes. The tabletop, transient gain x-ray lasers currently have the properties of picosecond pulse duration, coherence, short wavelength ~14.7 nm, and a few 10s of μJ output energy at high repetition rate [9]. This is sufficient for applying tabletop picosecond x-ray laser interferometry to laser-produced plasmas. Results are presented from recent experiments using a Mach-Zehnder type interferometer [7], with diffraction gratings as beam-splitters fabricated at Colorado State University, designed for the COMET picosecond, 14.7 nm soft x-ray laser.

2. X-ray laser generation and interferometry

The experiments were performed on the Compact Multipulse Terawatt (COMET) laser system at LLNL [9]. This laser, operating at 1054 nm wavelength, utilizes the technique of chirped pulse amplification to produce three high power beams of nominally 500 fs (compressed) and 600 ps (FWHM) pulse duration with a repetition rate of 1 shot every 4 minutes. The Ni-like Pd ion 14.7 nm x-ray laser is generated with two of these beams: the short pulse of 5 – 6 ps duration with energy of 4.5 – 6.5 J and the long pulse with typically energy of 0.5 – 2 J. The peak-to-peak delay between the laser pulses is found to be optimal at 700 ps with the short pulse arriving after the long pulse. The two laser pulses are delivered in a 1.65 cm long line focus. Traveling wave excitation geometry is implemented before the focusing optics by using a high-reflectivity, 0° dielectric-coated reflection echelon consisting of seven flat vertical mirror segments. This matches the short pulse excitation process to the propagation of the x-ray laser along the plasma column gain region.

The third 600 ps beam with 0.5 J generates a second line focus plasma in a separate vacuum chamber to be probed by the x-ray laser. This beam is focused to ~85 μm (FWHM) width by 0.6 cm length corresponding to an intensity of 1.7×10^{11} W cm^{-2} on target. The experimental layout for the Mach-Zehnder type Diffraction Grating Interferometer (DGI) is shown in Figure 1. The 14.7 nm x-ray laser beam is collimated by the 0° spherical, multilayer x-ray mirror *S1* and pointed by the 45° flat mirror *M1* along the input axis of the interferometer and onto the first optic grating *G1*. The beam pointing is checked with CCD1 (with *G1* out). The first Au-coated grating *G1*, 900 l/mm groove spacing, splits the XRL into a 0th order (plasma probe) arm and a 1st order (reference) arm. The grating blaze angle and geometry has been designed to have equal reflectivity of ~25% in each arm. The two orders are reflected by the Au-coated mirrors *L1* and *L2* to overlap the arms on the grating *G2*. The plasma to be probed is placed in the 0^{th} order beam. The spherical multilayer mirror *S2*, f = 25 cm, after *G2*, images the plasma and relays the beam via the output mirror *L3* to the camera CCD2. The system magnification is 9.3× giving a pixel limited resolution of 2.6 µm. The generated interference fringes were excellent indicating good longitudinal and transverse coherence of the x-ray beam. High fringe visibility, $V = (I_{max} - I_{min})/(I_{max} + I_{min})$, of 0.72 ± 0.12 was measured.

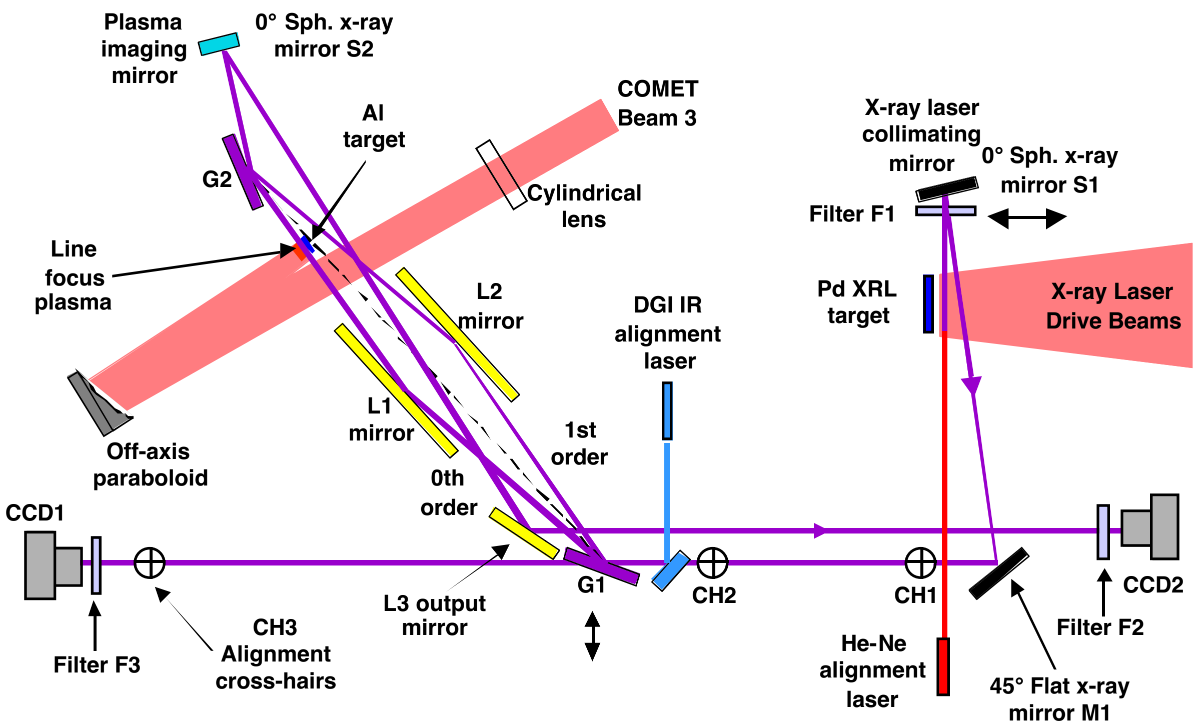

Fig. 1: Experimental setup for diffraction grating interferometer on the COMET x-ray laser facility. XRL is collimated by spherical mirror *S1* and sent via flat mirror *M1* along input axis of the DGI onto grating *G1*. XRL pointing is checked on the back-thinned camera CCD1 by translating *G1* out of beam and using cross-hair fiducials *CH1*, *CH2* and *CH3*. *G1* splits beam into 2 orders that are combined at *G2*. COMET Beam 3 with a 600 ps (FWHM) pulse is focused to a line focus on Al target in 0^{th} order arm. Spherical mirror *S2* images plasma and output mirror *L3* routes beam to a back-thinned camera CCD2.

3. Results

Figure 2(a) shows a 14.7 nm soft x-ray interferogram of a 400 × 400 µm^2 imaged region of a 0.5 cm long Al plasma heated by the 600 ps (FWHM), 1054 nm laser pulse. Target surface is at z=0 and the bright spot is the time-integrated plasma x-ray emission. A delay line on the plasma-forming beam is adjusted for the x-ray laser to probe the plasma at various times: results are shown for Δt = +0.5 ns after the peak of the heating pulse. The absolute timing of the heating and x-ray laser beams is known to better than 100 ps while the x-ray laser pulse duration is estimated to be ~6 ps. The critical density for the probe laser wavelength of 14.7 nm corresponds to n_{crit} = 5.09 × 10^{24} cm^{-3}. For a plasma with electron density, n_e, the index of refraction integrated along the column length in one arm of the interferometer will introduce a fringe shift in the interferogram as shown in Fig. 2(a). The fringe shift, N_{fringe}, can be measured over the two-dimensional field and the electron density determined provided the column length is known. This can be written as $N_{fringe} = 6.68 \times 10^{20}\ n_e\ L$ (n_e in cm^{-3}, L in cm) and so for 0.508 cm Al targets, one fringe shift corresponds to an electron density of 2.95 × 10^{19} cm^{-3}. A maximum of 4 fringe shifts, corresponding to $n_e \sim 1.2 \times 10^{20}$ cm^{-3} at z = 10 µm, is detected. Figure 2(b) is a one-dimensional density versus z plot through y = 0 for the interferogram shown in Figure 2(a). The error bars on the data points result from the uncertainty in the target surface of $\Delta z \sim \pm$ 5 µm and a minimum density increment of $\Delta n_e \sim 2.2 \times 10^{18}$ cm^{-3} associated with the fringe shift centroid finding method applied here. The plasma self-emission is brighter than the laser probe and prevents measurements closer than ~15 µm to the target surface. The electron density gradient out to z = 90 µm indicates a plasma scalelength of 40 µm. Recent experiments on shorter targets with further reduction of the self-emission have allowed us to probe much closer to the target surface. These initial experiments show that picosecond x-ray laser interferometry is a unique and powerful tool for diagnosing large, hot, dense plasmas and to benchmark hydrodynamic simulations codes. Further progress in the experiments and simulations will be discussed.

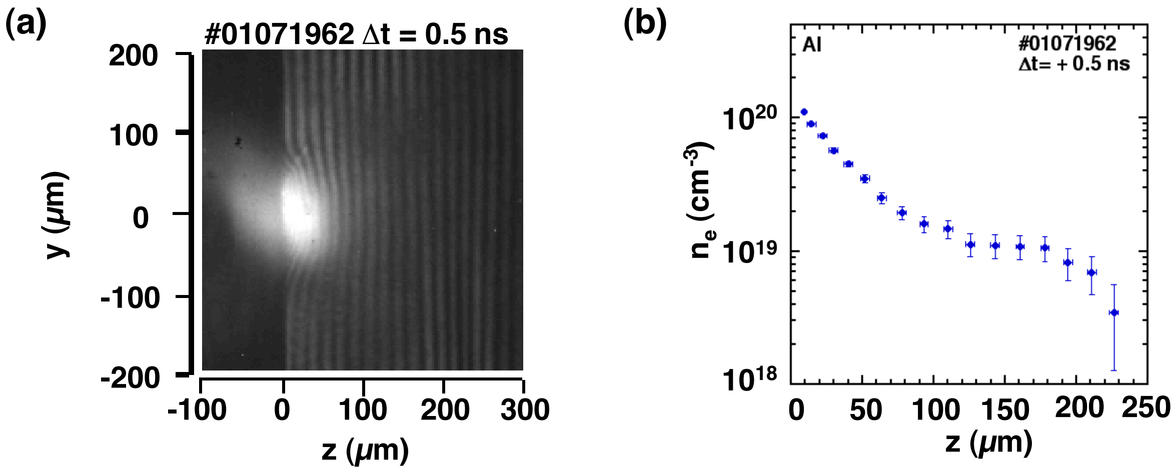

Figure 2: (a) X-ray laser interferogram probing a 0.5 cm Al plasma at Δt = +0.5 ns relative to the peak of the plasma-heating pulse. Target surface is at z = 0. (b) Electron density n_e versus z for a lineout through y = 0 for the interferogram shown in (a).

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